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The physical processes of seabed disturbance during iceberg grounding and scouring

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Abstract—Icebergs drifting in ocean currents over the Labrador continental shelf may contact and move through seabed sedi..ents to create characteristically curvilinear features, commonly referred to as scours, which average 1–2 m in depth and about 30–40 m in width. Such scours may continue for several hundreds of metres or several kilometres. The period of seabed interaction may last from a few minutes to several months and results in modification of both the seabed sediments and the iceberg keel. When observed from submersible soon after their formation, scours exhibit morphological characteristics not seen in old, degraded scours.

The scour trough, between two berm ridges, is generally flat-bottomed but is characterized by the presence of ridge-and-groove microtopography, with amplitudes up to 0.3 m developed parallel to the scour axis. These features are formed at the trailing edge of the keel by clastic material embedded in the ice and by open fissures in the ice. In places along the inner berm margins, ridges and grooves may be developed at an angle to the scour axis, reflecting lateral displacement of material towards the berm as the iceberg moves forward. Voids up to 1 m deep and 2 m wide occasionally truncate the ridges and grooves. Voids are formed following the dissolution of small (a few m^3) masses of debris-laden ice that are mechanically broken off from the base of the keel and pressed into the seabed by the scouring iceberg. Initially low areas within the scour trough may preserve seafloor that has not been affected by ice–seabed interaction. In these regions deposition of bulldozed sediment from the surcharge at the leading edge of the keel may partially fill the narrow spaces beneath the keel in areas of initially low seabed elevation.

Scour berms consist of *in situ* fractured but intact blocks of material on the inner flanks, and disarticulated blocks 1–2 m high along the berm crest. The outer berm slopes generally consist of pieces of larger blocks spalled from the berm crest resting in relatively finely comminuted, reworked material. The reworked material originates in the leading edge surcharge before being displaced to either side of the keel. Scour berms have irregular topography ranging in height from a few centimetres to as much as 6 m above the seabed. Isolated irregularly-shaped mounds beyond the outer berm may represent pieces of cohesive sediment that originated at the berm crest as overhangs and which subsequently collapsed.

INTRODUCTION

ICEBERGS may come into contact with the seabed in one of two ways. They may drift onto shoaling bank top areas, scouring or grounding occurring as draft exceeds water depth.

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Alternatively they may increase their draft by unstable roll, caused by ablation and/or minor calving events, or as the result of splitting of tabular icebergs.

Iceberg scours and pits, formed by ice–seabed interaction, have been observed on modern and ancient seabed and lake bed surfaces for many years (for example BELDERSON *et al.*, 1973; BELDERSON and WILSON 1973; HARRIS and JOLLYMORE, 1974; BERKSON and CLAY 1973). The morphologies of these old scours have been described from sidescan sonographs and high resolution sub-bottom profile data (for example LEWIS *et al.*, 1980; BARRIE, 1980; FADER and KING, 1981; STOKER and LONG, 1984; TODD *et al.*, 1988) and from direct observation using miniature submarines (for example JOSENHANS and BARRIE, 1989; FADER, 1989; LEWIS and FADER, 1985; JOSENHANS and BARRIE, 1982). Observations of iceberg scours on the eastern Canadian continental margin are summarized by LEWIS and WOODWORTH-LYNAS (1990). However few new iceberg scouring events have been observed and documented (for example PARROTT *et al.*, 1990).

This paper describes and interprets observations of the iceberg scouring process made during the Dynamics of Iceberg Grounding and Scouring (DIGS) experiment carried out on the Labrador continental shelf (Fig. 1) in 1985 (HODGSON *et al.*, 1988). DIGS was a multi-disciplinary study designed to make detailed observations and measurements of the iceberg grounding and scouring phenomenon ranging from the dynamic behaviour of free-floating and seabed-touching icebergs to descriptions and measurements of iceberg-deformed seabed sediment.

Five new iceberg scours ("Bertha" scour, "Big Makk" scour, asymmetric scour, "Caroline" scour and Baffin shelf scour, see Fig. 1) were documented during the DIGS experiments (Table 1). In addition an iceberg ("Gladys") was observed to impact the seafloor but no subsequent seabed observations could be made. Visual observations of the scours were made using the submersible PISCES IV and the character and extent of each scour was recorded by the use of high resolution 100 kHz sidescan sonar and by acoustic sub-bottom profiler data.

The "Bertha" scour was examined from the submersible 2 weeks after the iceberg grounded in 107 m of water on Makkovik Bank. The feature consisted of a pit where the iceberg had initially grounded and three "skip" mark scours made by the oscillating iceberg as it lifted off from the grounding pit. "Big Makk" was discovered in 150 m water depth as a fresh feature during a detailed sidescan sonar survey of a portion of north-western Makkovik Bank, and was subsequently investigated during two submersible dives. The scour was approximately 315 m long and 50 m wide.

An asymmetric scour was observed during a submersible transect at 138 m water depth on the western slope of Makkovik Bank. The "Caroline" scour was discovered in a repeat sidescan sonar survey of an older scour in 120 m water depth on Saglek Bank. Finally, an iceberg scour on the Baffin shelf was encountered during a submersible dive at 230 m water depth.

The objective of this paper is to describe and interpret the common elements of the five iceberg scours in order to gain a better understanding of the processes and mechanisms occurring at the keel–seabed interface. Elements unique to a site are also described: we believe these features can be found in other newly formed iceberg scours. Both common and unique elements are used to create a geological model of the scouring process that can be compared to ancient iceberg furrows.

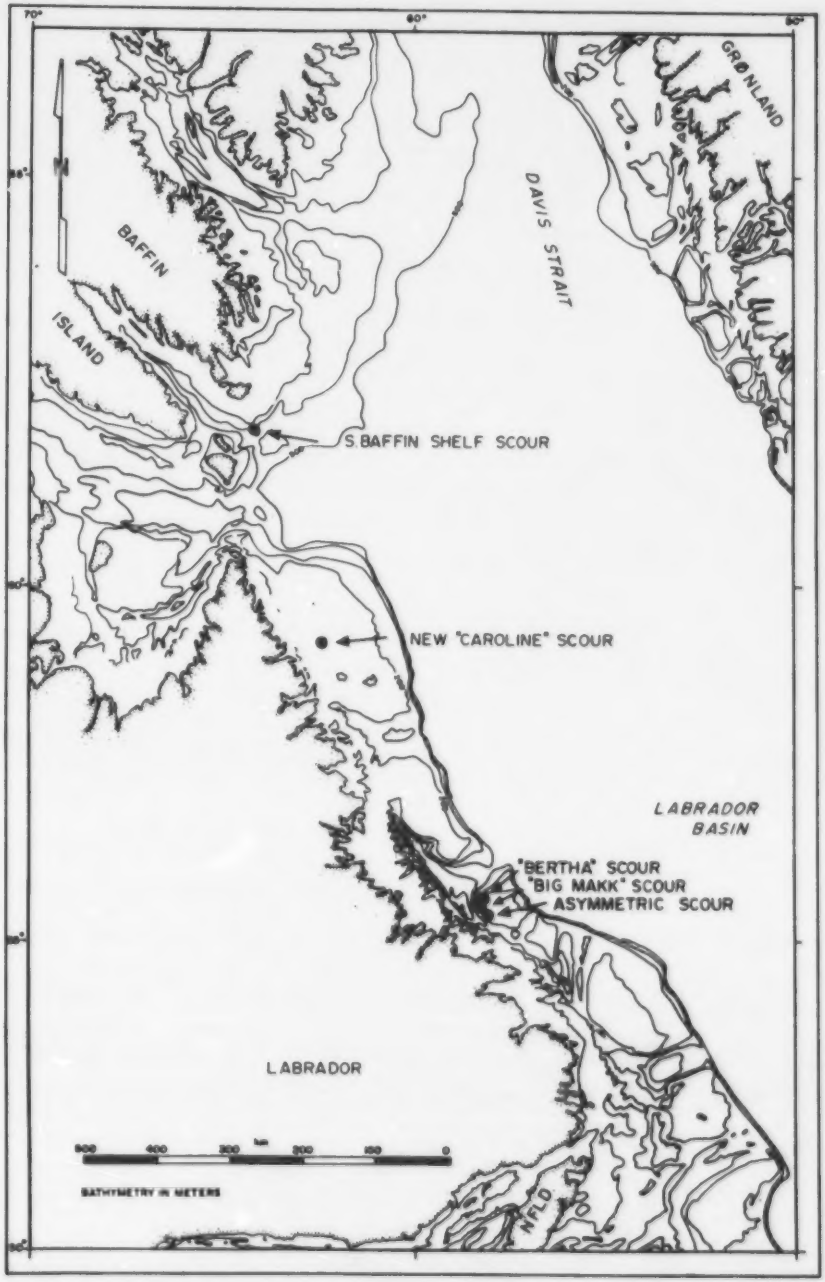

Fig. 1. Location map of the new iceberg scours and grounding site. Base map from General Bathymetric Chart of the Oceans (GEBCO), sheet 5.04, 1 : 10,000,000 (1984).

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GENERAL GEOLOGY

The area of study includes the tops of two of the six large, heavily iceberg-scoured banks which comprise the outer shelf regions of the Labrador Sea adjacent to eastern Canada. An additional site occurs north of this region on the southeast Baffin Island shelf. Water depths on the bank tops range from a minimum of 87, to 300 m. The banks are separated by transverse valleys or "saddles" up to 500 m deep. The bank tops are blanketed by post-glacial marine sediments of the Sioraq Sand (fine sand to muddy sand) and reworked Qeovik Silt (silt to sandy gravel) formations which overlie a series of at least three till units (JOSENHANS *et al.*, 1986). Iceberg scours described in this paper are developed in these overlying units.

ELEMENTS OF NEW SCOURS

Flat-bottomed scour troughs

Visual observations made from PISCES IV showed the troughs of all five scours to be essentially flat. Flat scour troughs indicate that the bases of the scouring keels were also flat. This interpretation was strengthened by observation of an overturned iceberg nearer

Table 1.

Site	Water depth	Sediment unit	Common elements	Unique elements
"Bertha" scour	107 m	Upper Till	RGM* Berms FBT†	Ice and boulder embedded in seafloor. Disjunct RGM* in first impact mark
"Big Makk" scour	150 m	Qeovik Silt Fm.	RGM* Berms FBT† Melt-out pits	Surcharge. Flat-topped mounds
Asymmetric scour	137.5 m	Upper Till	RGM* Berms FBT†	Berm on down-slope margin only
New "Caroline" scour	120 m	Qeovik Silt Fm.	RGM* Berms FBT† Melt-out pits	Disjunct RGM* on inner berm flanks
S. Baffin shelf scour	230 m	Fine sand	RGM* Berms FBT†	

*RGM = Ridge-and-groove microtopography.
†FBT = Flat-bottomed scour trough.

to shore which presented to view a sediment-covered, flat surface, interpreted to be the former keel which had previously been in contact with the seabed (Fig. 2).

During the study, iceberg "Gladys", an 8.9 million tonne tabular iceberg, split in two. One half immediately grounded in 134 m of water. About 7.25 h later an underwater calving event released several sediment-laden growlers from the grounded keel. The growlers, which contained seabed sediment entrained along numerous fractures, are interpreted to have originated from the edge of the keel where fractured ice, as in the overturned keel described above, would be likely to break off. Thin section analysis of ice samples show zones of fine-grained, euhedral, polygonal crystals in sharp contact with zones of large-grained crystals of undeformed glacier ice. The undeformed ice contains linear trains of elliptical air bubbles not seen in the fine-grained ice (Fig. 3). Also, thin (approximately 1 mm wide) fractures, filled with fine sediment, penetrate the zones of glacial ice crystals but do not occur in the fine-grained ice. However, fine sediment is concentrated along grain boundaries throughout the zones of fine-grained ice.

Features within the scour trough

Ridge-and-groove microtopography. Common to all five new scours are the presence of scour-parallel ridges and grooves. With relief and widths ranging from a few millimetres to 0.3 m, these features are developed on the inner berm flanks and in the scour troughs. The larger ridges and grooves are seen on 100 kHz sidescan sonographs (Fig. 4a) and can be traced for at least 500 m. The smaller ridges and grooves, seen only from PISCES IV (Fig. 4b) are less continuous, often dying out within a few metres. From PISCES IV fine striations were seen on the flanks, tops and bottoms of ridges and grooves.

As they are traced along-scour the morphology of individual ridges and grooves often changes. Typically these changes involve increases or reductions in amplitude between a ridge crest and the bases of adjacent grooves. Changes in width, possibly of several tens of millimetres, and corresponding changes in cross-sectional shape are seen. Smooth ridges may deteriorate over several metres, the ridge walls appearing progressively more "ragged", as if an insufficient volume of sediment was available for their construction. Ridges and grooves which change shape may regain their original, or similar, morphologies. Occasionally, new ridges may start abruptly on one side of a single boulder or cobble, whose cross-sectional shape may be mirrored by the ridge.

Along the inside berm flank, ridges and grooves of characteristically smaller scale than those in the scour trough may be occasionally developed at angles up to 45° to the scour axis. In the first of the impact marks made by iceberg "Bertha", ridges and grooves were developed as two discordant sets almost at right angles. Although one set can be related to the direction of movement of iceberg "Bertha", the other cannot.

Melt-out voids. In the floor of the grounding pit made by iceberg "Bertha" (Table 1) a partially buried boulder, rimmed by iceberg ice, was observed from PISCES IV (Fig. 5). the iceberg had moved off 2 weeks previously, illustrating how ice, which is buoyant, can remain entrained in seabed sediment. It follows that as the ice block melted or dissolved a cast would be preserved in the seabed, and the boulder would be gently deposited on the floor of the void.

Subsequent to this discovery small voids, up to 1 m deep and 2 m wide, were occasionally found in other scour troughs. The irregular-sided features interrupt ridge-and-groove

microtopography which may partially cap some voids as delicate overhangs around the edges. Boulders and cobbles are commonly found resting on but not embedded in void floors. These features are interpreted as the end product of ice melt-out or dissolution.

Flat-topped mounds. Irregularly-shaped flat-topped mounds, ranging in height from 0.5–0.75 m, were observed in low areas below the general level of the trough surface in "Big Makk" and are clearly defined on the 100 kHz sidescan sonograph of the scour (Fig. 6). Ridge and groove microtopography is developed on the flat mound surfaces. In the low area, the seabed, upon which the mounds are located, is characterized by concentrations of undisturbed gravel and shell debris, similar to undisturbed seabed immediately outside the scour.

Features at the scour margins

Berms. A mixture of cohesive and non-cohesive sediments form berm ridges on either side of the scour, rising from as little as a few centimetres to as much as 6 m above the undisturbed seabed. Berm height is often variable, ranging in one instance (asymmetric scour, western Makkovik Bank) from 1 to 6 m over a distance of only a few metres along the berm crest. Berm width may vary from a few tens of millimetres to 10 m. The asymmetric scour was remarkable in that there was no berm on the upslope side of the scour. Berm slopes may reach angles as steep as 45°.

Inner berm flanks generally have low amplitude (less than 50 mm relief) ridge-and-groove microtopography developed on the concave slopes which rise up from the scour trough. In places the relatively smooth surface is disrupted by a network of open fractures (Fig. 7) ranging from <10 mm to about 0.2 m wide. No offset is observed between the cracks. Where exposed the vertical crack surfaces display conchoidal and radial fracture patterns (Fig. 8). Open cracks and micro-cracks ramify the sediment in the inner berm region. Micro-cracks were revealed during attempts to sample berm material in the new "Caroline" scour with the PISCES IV manipulator arm. Pushing small corers into the sediment caused sudden expulsion of fine material into the water column along the micro-cracks.

Approaching the berm crest the open fractures widen, separating discrete blocks of sediment. No longer constrained by adjacent material these blocks may collapse towards the outer berm slope creating spectacular chaotic topography (Fig. 9). In this region some vertical and horizontal offset is apparent. The tops of the blocks are usually faintly striated. The transition from berm crest to outer berm slope may be abrupt where large blocks are not present. (Fig. 10).

Outer berm slopes consist of small (0.05–0.5 m wide) angular blocks and rounded lumps of cohesive material, some of which are clearly derived from disintegration of the large fractured blocks along the berm crest. The small blocks rest on or are partially buried in loose, unconsolidated sediment which characterizes the outer slope. Isolated mounds or sub-angular blocks, 1–2 m^3 in volume, are occasionally found resting on undisturbed seafloor immediately beyond the lower berm slope. These appear to have originated from the berm crest.

Surcharge. "Big Makk" is a complete, short scour (315 m long), which provided a rare opportunity to observe the intact surcharge of sediment piled up in front of the scouring

Fig. 2. Photograph of an overturned iceberg whose flat, sediment-covered keel had been in contact with the seabed. Sediment grain size ranges from large boulders (approximately 0.5 m diameter), cobbles and probably pebbles and fines. Note the concentration of fine sediments along pronounced fractures in the ice at the edge of the keel. The field of view is approximately 10 m across. (Photo courtesy of Denny Christian, C-CORE.)

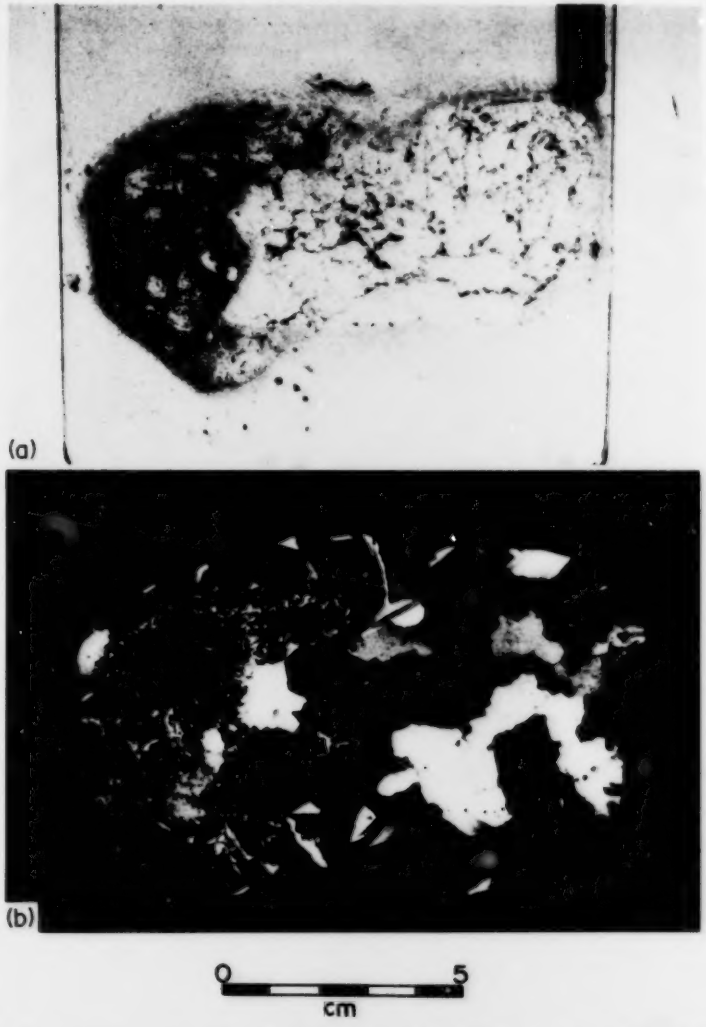


Fig. 3. Photomicrographs of a thin section of ice from a sediment-laden growler which calved from the grounded keel of iceberg "Gladys" (a, plane polarized light; b, polarized light). Note pervasive fracture planes running across the section. Fine-grained sediment is confined to fracture planes affecting original glacier ice crystals and to the grain boundaries in the fine-grained ice. Large porphyroclasts of relatively undeformed glacial ice are clearly evident and contain no sediment.

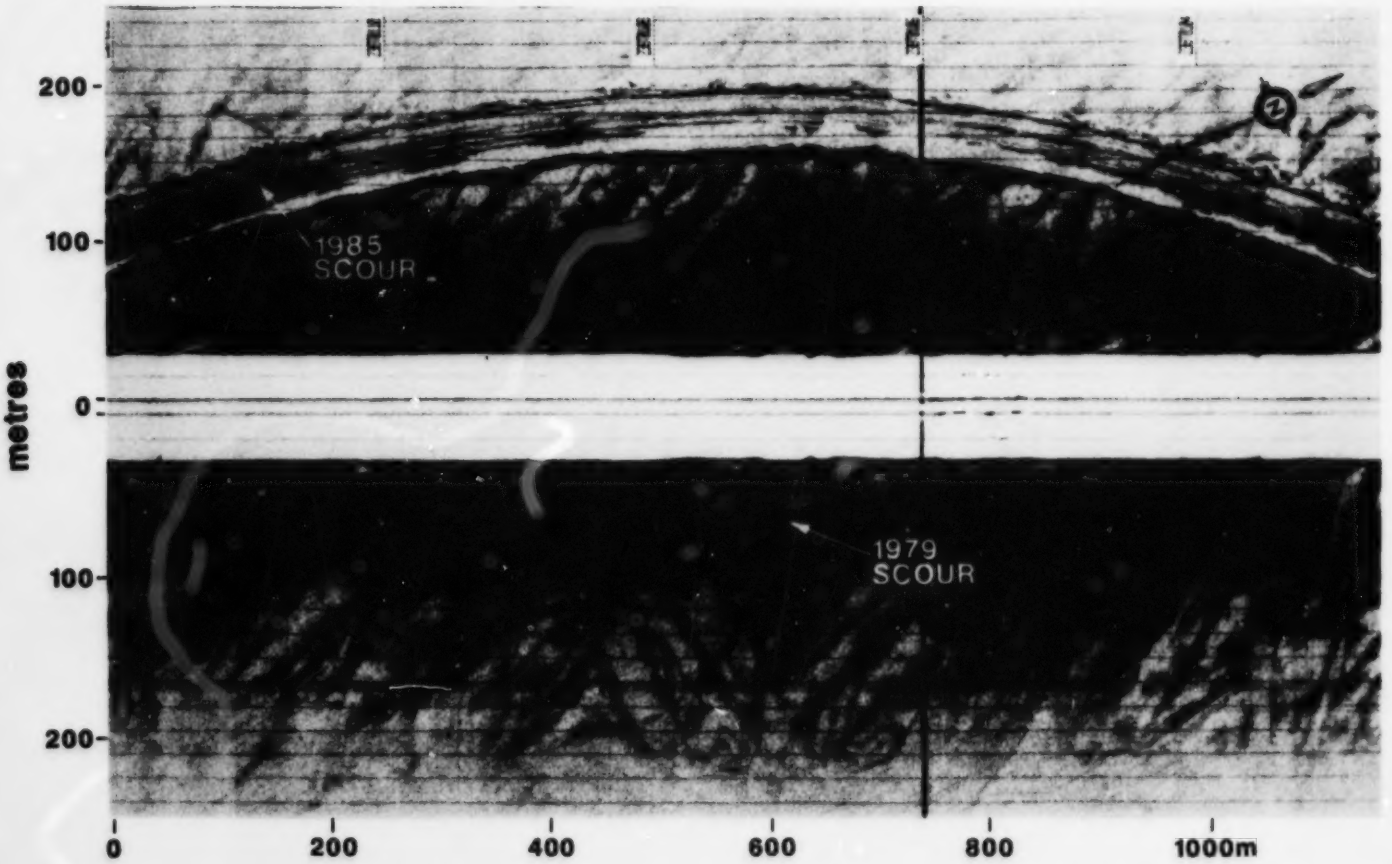


Fig. 4. (a) 100 kHz sidescan sonograph of the new "Caroline" scour (labelled "1985 scour") on Saglek Bank showing characteristic scour parallel ridge-and-groove microtopography. Some of the ridges and grooves can be traced for at least 500 m before dying out. Water depth 120 m.

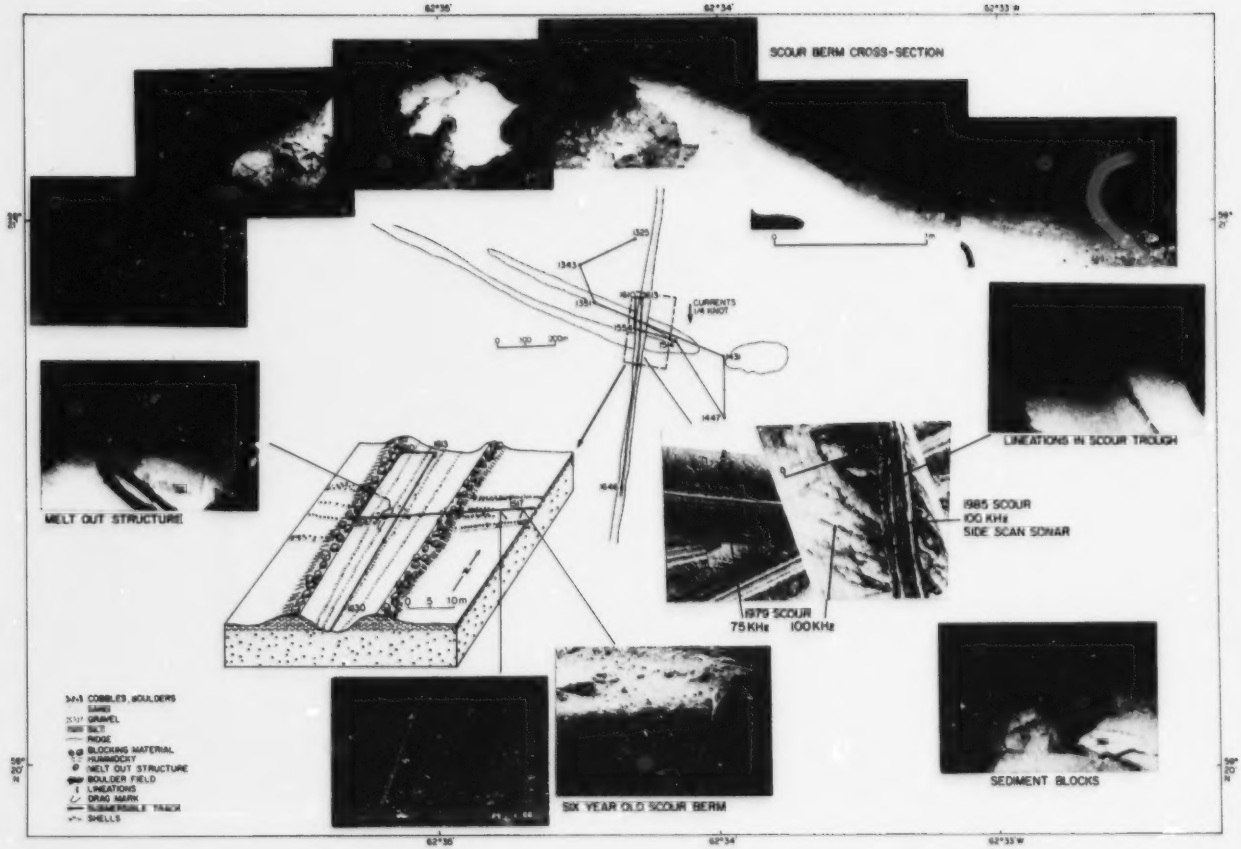


Fig. 4 *continued*. (b) Composite diagram and photomosaic (as seen from PISCES IV) from the outer berm (left) to scour trough (right) of the new "Caroline" scour (from JOSENHANS and BARRIE, 1989).

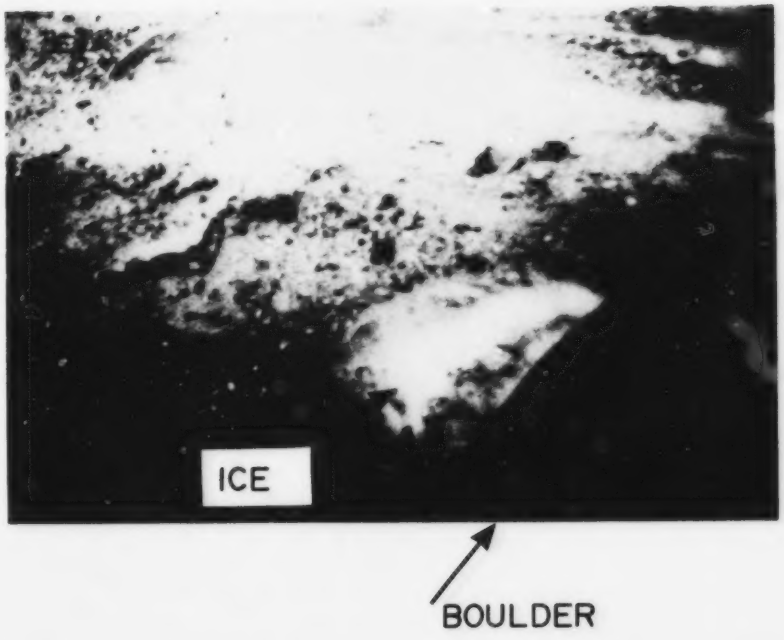


Fig. 5. Boulder, rimmed by ice, in seafloor sediments in the grounding pit made by iceberg "Bertha". Water depth 107 m.

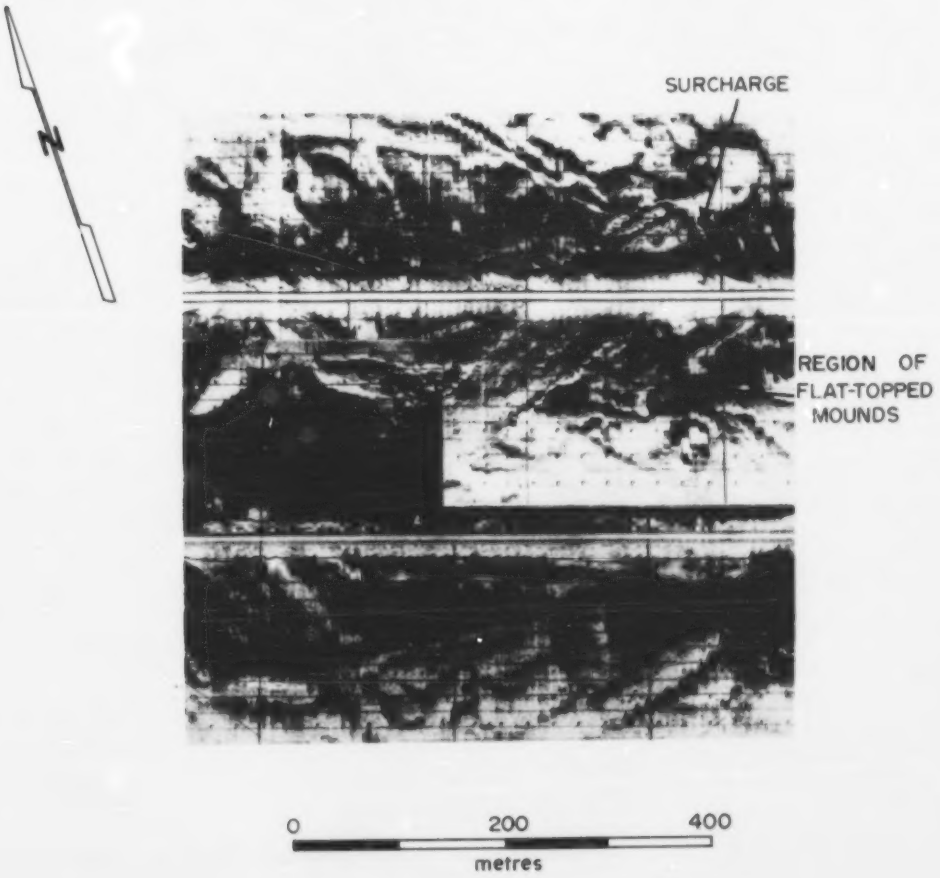
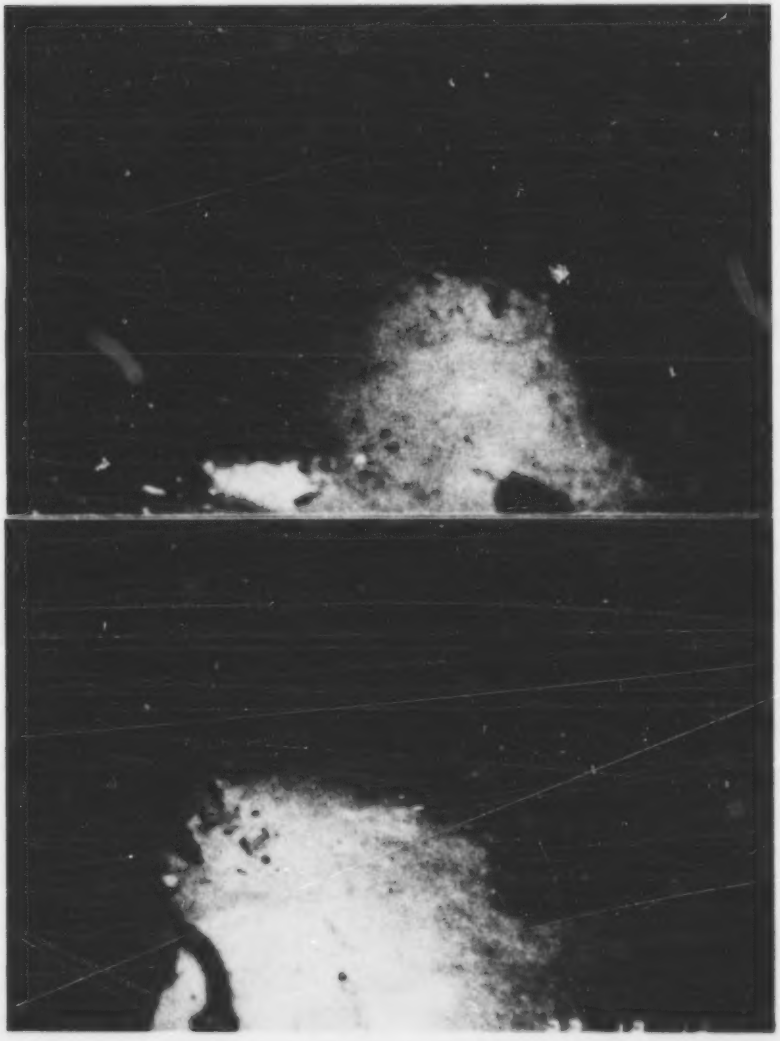


Fig. 6. (a) 100 kHz sidescan sonograph of the "Big Makk" scour showing the region of flat-topped mounds (arrows) in a depressed area approximately 100 m long and 20 m wide within the scour trough. The waviness of the ridge-and-groove microtopography is an artifact caused by yawing of the sidescan towfish. (b) Flat-topped mounds in "Big Makk" as they appear from PISCES IV. Field of view in each case is about 3 m across.



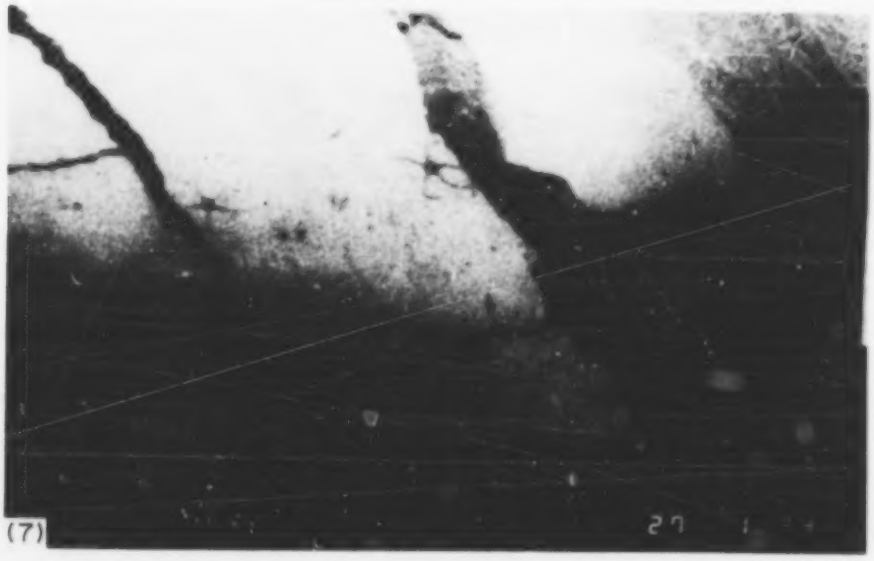


Fig. 7. Network of open fractures on the lower inner berm flank, new "Caroline" scour, Saglek Bank. Note presence of brittle stars. Field of view about 3 m across.

Fig. 8. Radial fracture pattern on a crack surface on the berm of the new "Caroline" scour, Saglek Bank. Field of view about 3 m across.

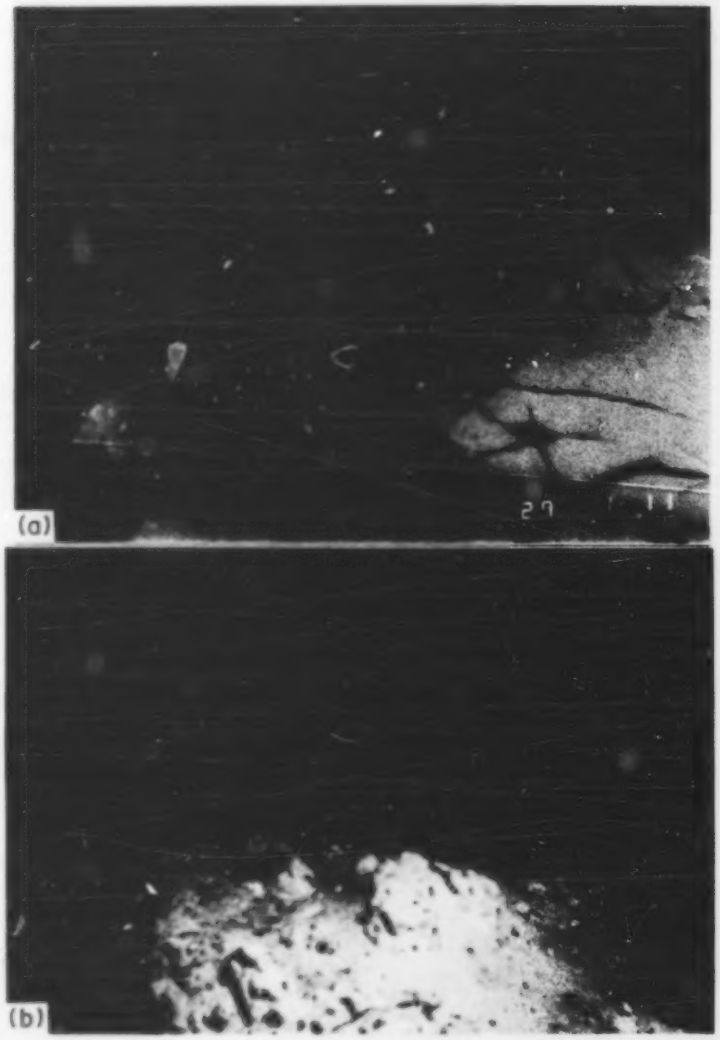


Fig. 9. (a) View of fractured, consolidated blocks of sediment at the crest of the new "Caroline" scour. Individual blocks rise about 1 m above the general level of the berm. Note presence of brittle stars. (b) Partially degraded cohesive sediment blocks on the berm of "Big Makk". Field of view in both cases is about 3 m across.

Fig. 10. Abrupt inner berm (right)/outer berm (left) transition. Large fractured blocks are not present in this region of the new "Caroline" scour berm. Small blocks resting on the loose outer berm slope material probably spalled from the cohesive inner berm. Note presence of brittle stars. Field of view about 3 m across.

keel. The surcharge pile, rising to 3.5 m above the seabed, was characterized by steep (30°) inner and outer slopes of lumpy, unconsolidated sediment. The top of the pile was rough and undulatory. Blocks of sediment, as seen in the berms, were nowhere evident.

INTERPRETATION AND MODEL

The above descriptions are compiled from features found in the new scours studied during the DIGS experiment. Not all scours display the same features, and some features are unique to specific scours (see Table 1). Bearing in mind that the data set consists of observations from a total of only five new iceberg scours it is possible that elements which are here described as unique may occur in other new scours.

All of the elements are incorporated in a mechanistic and predictive geological model for the development of surface morphology of new scours. From the model inferences are made about the interactive processes of seabed and iceberg modification.

Summary description

A typical new iceberg scour from the Labrador shelf consists of an essentially flat-bottomed trough incised up to 2 m into seafloor sediments. The trough between the two berms is characterized by scour-parallel ridge-and-groove microtopography. On inner berm flanks ridges and grooves may be at discordant angles to the scour trough. Irregular, small voids are found occasionally in the scour trough, and are the result of melting or dissolution of pieces of iceberg ice embedded in the seafloor. Coarse clastic debris in the bottom of the voids was probably introduced with the ice. Flat-topped mounds may occur in areas of negative relief below the depth of keel penetration. Seabed between the mounds may be unaffected by scouring.

Cracks may be observed on the inner berm flanks. Cracks widen towards the berm crest separating free-standing, straight-sided vertical or tilted blocks of consolidated sediment which create irregular berm topography. Outer berm slopes consist of unconsolidated sediments containing small, angular blocks of cohesive material derived from partial collapse of larger blocks along the berm crest. Blocks or irregular mounds of sediment may occur resting on undisturbed seabed beyond the outer berm slopes.

Surcharge, developed in front of the scouring keel, consists of unconsolidated sediment with irregular hummocky topography. Cohesive sediment blocks are not associated with the surcharge.

MODEL OF SCOURING

We suggest likely mechanisms, affecting both iceberg and seabed, which create the features described from new iceberg scours. Prediction of the types of features that will be produced and the formative mechanisms that are to be expected during scour is implicit in the model.

Likely scouring mechanisms

Keel flattening. The scouring keel of an iceberg exerts both vertical and horizontal forces on the seabed (for example Lever, 1986). If seabed sediments are weaker than the scouring keel these forces result in vertical penetration of the keel and horizontal and

vertical components of displacement of seafloor sediments as the iceberg moves forward. In steady state scouring a characteristically curvilinear trough of relatively uniform depth is excavated on the seafloor.

The flatness of the scour troughs indicates that the scouring keel must also have been flat. Given the irregular three-dimensional geometries unique to each iceberg, and the random probability that any portion of the iceberg may, by unstable rolling, become a seabed-touching keel, it is unlikely that every keel will be fortuitously flat in the plane of the seafloor at the instant of contact. Therefore it is likely that the processes of ice–seabed interaction modify the shape of the scouring keel possibly until an equilibrium condition is reached, presumably when keel penetration stabilizes at a depth where keel modification ceases. The flat bottom of the asymmetric scour which conforms to the seabed slope on western Makkovik Bank additionally suggests that the attitude of the flattened keel may develop as a function of seabed slope.

Keel modification was demonstrated by observation of an overturned iceberg (see Fig. 2). In this example of an iceberg keel interpreted to have been in seabed contact, the smooth ice slopes around the keel are truncated at the margin of the debris-laden surface, suggesting the former presence of ice in the region above the flat surface.

Further evidence of keel modification comes from the underwater calving event of iceberg "Gladys" which released sediment-impregnated growlers interpreted to have originated from the edge of the grounded keel. In this instance the growlers are evidence that ice is removed from the keel by fracturing and break-off of blocks. Fracturing is clearly seen in the overturned iceberg (see Fig. 2) and from this photograph it is easy to envision blocks breaking off around the edge of the keel. Thin sections of ice retrieved from a growler interpreted to have calved from the keel of "Gladys" reveal a two stage sequence of events (see Fig. 3): (1) initial brittle fracturing and cracking and simultaneous injection of fine-grained sediment along the cracks as the iceberg strikes the seabed (this phase probably results in the generation of blocks of ice which may subsequently break out of the keel) followed by (2) dynamic recrystallization of the large glacial ice grains resulting in the development of domains of small, polygonal grains as a result of continued loading experienced by the grounded keel. Fine-grained sediment is incorporated between grain boundaries. Cracks are not formed during this phase.

Although scours recorded on sidescan sonographs and high resolution seismic profiles may differ widely from each other, individual scours usually display relatively constant width, depth and morphology. The limited variance in shape and dimensions of individual scours reflects keel–seabed equilibrium suggesting that, in relative terms at least, the keel-flattening process is rapid and occurs near the start of the scour. Additional evidence for rapid keel flattening may be present at the "Big Makk" scour. The direction of iceberg movement is interpreted to have been towards the northeast from the existence of a surcharge mound at that end (Fig. 6a), and a smooth, sloping ramp at the southwest end of the 315 m long scour. In order to generate a flat surface at the lead-in portion of the scour the keel must have either been coincidentally flat in the plane of the seafloor or, as the more likely postulate, the keel was flattened during the initial interaction. This being so, the flattening process must have occurred rapidly.

A reasonable average drift velocity of the iceberg which formed "Big Makk" might be 0.56 m s^{-1} (1.1 knots) (for example Ball *et al.*, 1981). If we assume this velocity and that its keel was of similar length to its width (50 m as measured from the width of "Big Makk") then the amount of time taken for the centre of the keel to pass over a single spot on the

seabed would be about 90 s. If these conditions are valid then during this time the keel would have to have developed a flat base in order to create a flat lead-in ramp.

After initial rapid keel modification steady-state scouring occurs. Width and depth remain nearly constant during this period and the keel undergoes only minor, but probably continual modification: this is exemplified by the sporadic occurrence of small melt-out voids which indicate breakout of relatively minor ice volumes (up to about 2 m^3).

Formation of ridge-and-groove microtopography. The ridges and grooves developed within the scour trough are the result of the sculpting of sediment by irregularities in the scouring keel. Although the entire flattened surface of a scouring keel is probably in contact with the seabed, it is the relief of the trailing edge which generates the ridges and grooves. Relief of ridges and grooves is interpreted to directly mirror the irregularities in the trailing edge of the keel. Irregularities of similar magnitude probably characterize the entire surface of the scouring keel (as exemplified in Fig. 2) and, as it moves over the seabed, sediment adjacent to the keel is moulded and remoulded before it is finally shaped at the trailing edge.

During and after initial touchdown, ice in the keel is fractured and crushed and fine sediment is entrained (see above). If present on the seafloor, gravelly to bouldery clastic material may also be incorporated and held at the surface of the scouring keel (see Fig. 2). Clastic debris and fractured ice are thus the most likely factor affecting keel topography and which thus generate ridge-and-groove microtopography in the sediment of the scour trough. Boulders are occasionally released onto the seabed at the trailing edge of the keel. When this happens a void is created in the iceberg keel at the site of the boulder, into which sediment may be forced from the underlying seabed. If the void remains stable and there is sufficient sediment supply to fill the void as the keel moves forward, a ridge will be developed. Boulders at the beginnings of ridges thus mark the point of ridge initiation and indicate the direction of iceberg movement. If there is insufficient sediment supply to completely fill the voids and ice fissures the resultant ridges will be incomplete and may appear "ragged". New cracks may open and close in the ice, and boulders embedded in the keel may rotate or break out because of continued fracturing, crushing and refreezing, dynamic recrystallization and possibly pressure melting of the ice (for example Hobbs, 1974). These dynamic processes are reflected by gradual changes in the morphology and relief of ridges and grooves as they are traced along the scour.

Ridges and grooves within the main portion of the scour trough are nearly always parallel to the axis of the scour reflecting the rotational stability of the scouring iceberg about a vertical axis. This observation supports the inferred dynamic behaviour of a scouring iceberg which is that the iceberg yaws so that roll occurs about its weakest axis of rotation (Hodgson *et al.*, 1988). Once this condition is achieved, vertical rotations cease (for example Woodworth-Lynas *et al.*, 1985).

Formation of melt-out voids. Blocks of ice may be formed by fracturing of the keel and, if at a free surface such as at the margin of the keel (see Fig. 2), may break off and float free (for example, the growlers calved from iceberg "Gladys"). The unusual ridges and grooves at 90° to the dominant movement-related set in the first of the impact marks made by iceberg "Bertha" are possible evidence of the failure of a block of ice which was displaced outwards at a high angle from beneath the keel. Blocks which break out beneath the keel are prevented from floating and will be overridden and driven into the seabed by the

iceberg. Because these blocks originate from the scouring surface of the keel they may contain boulders and cobbles incorporated earlier: they may also contain original englacial clasts from the parent glacier. Subsequent melting or dissolution of the embedded ice blocks results in the formation of melt-out voids.

Formation of flat-topped mounds. As a scouring iceberg moves over an undulatory seabed (such as one affected by older scours) it is possible for the iceberg to pass over open depressions which are below the penetration depth of the keel. As the iceberg approaches, material from the leading edge surcharge is bulldozed into the depression ahead of the keel. The bulldozed material is subsequently overridden and reworked as the keel passes over it. In places where there has been incomplete filling of the depression, irrregularly-shaped masses of sediment may be found resting on the old seabed which is exposed in the regions surrounding them. Sediment masses will have planar grooved upper surfaces, formed through direct contact with the flat keel, and these surfaces will be at the same elevation as the rest of the scour trough (Fig. 6).

Formation of berms and surcharge. There is little doubt that most of the material which forms the berms originates from the seabed in the area formerly occupied by the scouring keel. Horizontal translation of the keel through the seabed causes most of the sediment to be displaced to the front and sides of the keel (e.g. the sediment surcharge piled up at the forward end of the "Big Makk" scour). Together with horizontal movement an upward component of displacement is implicit because the berms form positive relief. Depending on sediment type (in this case, generally sandy mud), cohesion, confining pressure and strain rate, sediment in front of the keel may behave initially as "rigid" slabs such as have been observed in excavated cross-sections of relict scours in southern Manitoba (WOODWORTH-LYNAS and GUIGNE, 1990), decoupling from the seabed along failure planes, the slabs being pushed radially away from the advancing keel. Slabs at the lateral margins of the keel may be displaced, intact, to the edge of the scour where their upper surfaces, having been in direct contact with the sediment-impregnated keel, form characteristically smooth, striated inner berm slopes.

Cracks on the inner berm slopes perhaps develop as the result of stress release as sediment is expelled from beneath the edges of the keel. Alternatively shear between the moving keel and the sediment may cause cracking and tensional dilation. The deep-seated cracks result in creation of often spectacular "blocky" berm topography.

Slabs in front of the keel are confined by surcharge material on either side and pushed further forward. As it continues forward new failure surfaces develop in seabed sediments in front of the keel. The older slabs are displaced upwards as new slabs, underneath, move forward and up, thereby generating a surcharge pile. As frontal slopes steepen the slabs begin to break up, possibly along tension cracks induced by components of displacement to either side of the keel and as the result of gravity-induced collapse, to form an apron of disaggregated material. Disaggregation processes may be so efficient as to cause almost complete reworking. This process may occur through a recycling mechanism where material at the top of the surcharge slope cascades down in front of the keel. Continued forward motion, which causes fresh sediment to be added beneath the surcharge pile, causes the passive movement of spalled material towards the top of the surcharge slope, where it will again cascade forwards and downwards. Such a "conveyor-belt" type of action may allow several episodes of recycling to occur before the material is eventually displaced to either side of the keel where it generates the outer berm slopes.

SUB-SCOUR EFFECTS

The model presented here describes the likely mechanisms of scour formation based solely on descriptions of scours as they appear at the seabed on the Labrador and Baffin Island shelf. Sediment deformation below, to the sides and in front of the keel are implied from the observations, but examination of sub-scour deformational effects and structures is difficult using submersibles.

To solve the problem of access beneath scours WOODWORTH-LYNAS and GUIGNE (1990) excavated and described structures from beneath relict iceberg scours exposed on the former bed of glacial Lake Agassiz in southeast Manitoba. Beneath one scour they describe deep-rooted low angle faults with demonstrable strike-slip offsets of 3.5 m. POOROOSHASB *et al.* (1989) interpret these as possible normal faults similar to those which develop during shallow foundation failure. Slabs of sediment, originating from the scour trough, are stacked along horizontal thrust faults to build the berms. At the berm crest a collapsed block was seen and this may be analogous to the "blocky" berms seen in the Labrador Shelf scours. The Lake Agassiz scours are developed in very fine clays and thus caution is used in transposing deformation mechanisms from this situation to scours in the sandy silt facies prevalent on the Labrador Shelf. POOROOSHASB *et al.* (1989) demonstrated incremental downward displacement of laminae at depths in the soil up to five times the scour incision depth in model experiments using saturated silts. In another test with deeper keel penetration they observed apparent complete reworking and obliteration of laminae beneath the scour.

These observations, derived empirically from both actual and modelled scours, confirm that deformation occurs in sediments beneath scouring iceberg keels. These "cross-sectional" views are required before complete integration of this approach with the "surface morphology" approach can be achieved. First, analysis of relict scours developed in soils, similar to those found in offshore areas where scouring is an active process, is relevant because soil properties will affect the mode of deformation. Second, the effects of scour width-to-depth ratio need to be taken into account; a very wide keel may disperse the vertical load over such a large area that sub-keel effects are negligible, conversely narrower keels may concentrate greater downward stresses into sediments causing sub-keel deformation (J. CLARK, personal communication, 1989). A study of relict scours with a range of widths is thus appropriate. This should be done in conjunction with an analysis of sidescan and sub-bottom profiles of wide and narrow new scours which may reveal morphological divergences.

SUMMARY

From detailed analyses of five new iceberg scours a descriptive and mechanistic model of scours and the scouring process has been developed. The model is summarized as follows:

(1) As the keel of an iceberg contacts the seabed it penetrates seabed sediments. During the interaction the shape of the keel is modified and flattened both by fracturing and breaking off of blocks of ice and by dynamic recrystallization. Initial flattening may be rapid (possibly tens of seconds) involving the loss of significant volumes of ice. An equilibrium state is achieved when keel modifying processes and the depth of seabed penetration are balanced. An equilibrium is reflected by maintenance of constant scour width and scour depth. Blocks of ice at the margin of the keel may be expelled and float to

the surface. Blocks broken off at the keel–sediment interface may be driven into the seabed; subsequent melting or dissolution, days or possibly weeks after the scouring event creates melt-out voids.

(2) Ridge-and-groove microtopography in the scour trough is generated at the trailing edge of the keel by clastic material embedded in the ice and by direct contact with fractured ice. Following the breakout of boulders from the trailing edge of the keel, seabed sediment may be forced into the newly-created voids in the keel as the iceberg moves forward initiating a ridge; boulders lodged at the start of ridges indicate the direction of iceberg movement. The area of the keel in contact with the seabed is impregnated with clastic material largely derived from interaction with the seabed. Some material may also be englacial in origin. As the keel passes through the seabed subjacent sediment is moulded and remoulded before final shaping at the trailing edge. The probability that seabed sediment adheres to an iceberg keel during a scouring event implies that ice-rafted detritus deposited from melting icebergs may not necessarily originate from glaciated terrains, but may be material recycled from continental shelves within the dispersal route of icebergs.

(3) As the keel passes over minor depressions that are lower than the depth of penetration, material derived from the surcharge pile may fill the sub-keel void. Incomplete filling results in depressed areas of undisturbed seabed within the scour trough which contain "lumps" of sediment, the upper surfaces of which are planed off through direct contact with the keel.

(4) Cohesive sediment at the lateral margins of the keel is displaced to either side with both horizontal and vertical components of movement. As it emerges from beneath the keel, stress release and shear stress between the keel and the sediment may cause cracking and separation of the sediment into discrete blocks. Fractured sediment displaced to the berm crests may collapse under gravity generating a highly irregular "blocky" berm crestline. Sediment in front of the keel may be recycled in a "conveyor-belt" type of action. The disaggregated material which results is displaced laterally forming the outer berm slopes and the substrate upon which sediment blocks, originating from the sides of the scouring keel, are deposited.

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REFERENCES

BALL P., H. S. GASKILL and R. J. LOPEZ (1981) *Iceberg motion: an analysis of two data sets collected at drill sites in the Labrador Sea*. C-CORE Technical Report 81-2, 121 pp.

BARRIE J. V. (1980) Iceberg–seabed interaction (northern Labrador Sea). *Annals of Glaciology*, **1**, 71–76.

BELDERSON R. H. and J. B. WILSON (1973) Iceberg plough marks in the vicinity of the Norwegian Trough. *Norsk Geologisk Tiddskrift*, **53**(4), 323–328.

BELDERSON R. H., N. H. KENYON and J. B. WILSON (1973) Iceberg plough marks in the northeast Atlantic. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **13**(3), 215–224.

BERKSON J. M. and C. S. CLAY (1973) Microphysiography and possible iceberg grooves on the floor of western Lake Superior. *Geological Society of America Bulletin*, **84**(4), 1315–1328.

FADER G. B. J. (1989) Submersible observations of iceberg furrows and sand ridges, Grand Banks of Newfoundland. In: *Submersible observations off the east coast of Canada*, D. J. W. PIPER, editor, Geological Survey of Canada Paper 88–20, pp. 27–39.

FADER G. B. and L. H. KING (1981) *A reconnaissance of the surficial geology of Grand Banks of Newfoundland*. Current Research, Part A, Geological Survey of Canada Paper 81-1A, pp. 45–56.

HARRIS I. M. and P. G. JOLLYMORE (1974) Iceberg furrow marks on the continental shelf northeast of Belle Isle, Newfoundland. *Canadian Journal of Earth Sciences*, **11**(1), 43–52.

HOBBS P. V. (1974) *Ice physics*. Clarendon Press, Oxford, 837 pp.

HODGSON G. J., J. H. LEVER, C. M. T. WOODWORTH-LYNAS and C. F. M. LEWIS (editors) (1988) *The Dynamics of Iceberg Grounding and Scouring (DIGS) experiment and repetitive mapping of the eastern Canadian continental shelf*. Environmental Studies Research Funds Report No. 094, Ottawa, 316 pp.

JOSENHANS, H. W. and J. V. BARRIE (1982) *Preliminary results of submersible observations on the Labrador shelf*. Geological Survey of Canada Paper 82-1B, pp. 269–276.

JOSENHANS H. W. and J. V. BARRIE (1989) Submersible observations on the Labrador shelf, Hudson Strait and Baffin shelf. In: *Submersible observations off the east coast of Canada*, D. J. W. PIPER, editor, Geological Survey of Canada Paper 88–20, pp. 41–56.

JOSENHANS H. W., J. ZEVENHUIZEN and R. A. KLASSEN (1986) The Quaternary geology of the Labrador Shelf. *Canadian Journal of Earth Sciences*, **23**(8), 1190–1213.

LEVER J. (1986) Iceberg dynamics of the DIGS experiment. In: *Ice scour and seabed engineering*, C. F. M. LEWIS, D. R. PARROTT, P. G. SIMPKIN and J. T. BUCKLEY, editors, Environmental Studies Revolving Funds Report No. 049, Ottawa, pp. 138–142.

LEWIS C. F. M. and G. B. FADER (1985) *Submersible observations of iceberg furrows in glacial till, northeast Newfoundland shelf; and in sand and gravel, Grand Banks of Newfoundland* (Abstract). Workshop on Ice Scouring, National Research Council of Canada Technical Memorandum No. 136, p. 101.

LEWIS C. F. M. and C. M. T. WOODWORTH-LYNAS (1990) Ice scour. In: *Geology of the continental margin of eastern Canada*, M. J. KEEN and G. L. WILLIAMS, editors, Geological Survey of Canada. Geology of Canada No. 2 (Also, Geological Society of America, The geology of North America, v. I-1), pp. 785–793.

LEWIS C. F. M., B. MACLEAN and R. K. H. FALCONER (1980) *Iceberg scour abundance in Labrador Sea and Baffin Bay; a reconnaissance of regional variability*. First Canadian Conference on Marine Geotechnical Engineering, 25–27 April 1979, Calgary, The Canadian Geotechnical Society, Montreal, pp. 79–94.

PARROTT D. R., C. F. M. LEWIS, E. BANKE, G. B. J. FADER and G. V. SONICHSEN (1990) *Seabed disturbance by a recent* (1989) *iceberg grounding on the Grand Banks of Newfoundland*. Current Research, Part B, Geological Survey of Canada, Paper 90-1B, pp. 43–48.

POOROOSHASB, F., J. I. CLARK and C. M. T. WOODWORTH-LYNAS (1989) *Small scale modelling of iceberg scouring of the seabed*. Proceedings of the 10th International Conference on Port and Ocean Engineering under Arctic Conditions, 12–16 June, Lulea, Sweden, Vol. 1, pp. 133–145.

SCHOENTHALER L. (1986) In: *Ice scour and seabed engineering*, C. F. M. LEWIS, D. R. PARROTT, P. G. SIMPKIN and J. T. BUCKLEY, editors, Environmental Studies Revolving Funds Report No. 049, Ottawa, pp. 200–203.

STOKER M. S. and D. LONG (1984) A relict ice-scoured erosion surface in the central North Sea. *Marine Geology*, **61**, 85–93.

TODD B. J., C. F. M. LEWIS and P. J. C. RYALL (1988) Comparison of iceberg scour marks with iceberg trajectories and evidence of paleocurrent trends on Saglek Bank, northern Labrador shelf. *Canadian Journal of Earth Sciences*, **25**(9), 1374–1383.

WOODWORTH-LYNAS C. M. T. and J. Y. GUIGNE (1990) Iceberg scours in the geological record: examples from glacial Lake Agassiz. In: *Glacimarine environments: Processes and sediments*, J. A. DOWDESWELL and J. D. SCOURSE, editors. Geological Society Special Publication, No. 53, pp. 217–233.

WOODWORTH-LYNAS C. M. T., A. SIMMS and C. M. RENDELL (1985) Iceberg grounding and scouring on the Labrador continental shelf. *Cold Regions Science and Technology*, **10**, 163–186.